

Estimating the Reliability of Electronic Parts in High Radiation Fields

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Abstract: Radiation effects on materials and electronic parts constrain the lifetime of flight systems visiting Europa. Understanding mission lifetime limits is critical to the design and planning of such a mission. Therefore, the operational aspects of radiation dose are a mission success issue. To predict and manage mission lifetime in a high radiation environment, system engineers need capable tools to trade radiation design choices against system design and reliability, and science achievements. Conventional tools and approaches provided past missions with conservative designs without the ability to predict their lifetime beyond the baseline mission. This paper describes a more systematic approach to understanding spacecraft design margin, allowing better prediction of spacecraft lifetime. This is possible because of newly available electronic parts radiation effects statistics and an enhanced spacecraft system reliability methodology. This new approach can be used in conjunction with traditional approaches for mission design. This paper describes the fundamentals of the new methodology.

Keywords: Europa, Radiation, Reliability, Probabilistic Risk Assessment (PRA)

1 EUROPA EXPLORER MISSION (TAKING NECESSARY RISKS)

Europa is a geophysical wonderland for space exploration due to its large, warm, salty ocean. It not only captures the imagination of the general public but it is also scientifically important. NASA has been studying concepts for a potential explorer mission designed to investigate Europa and the Jovian system. An orbiting spacecraft with a capable payload would explore Europa, assess its habitability and provide close examination of this fascinating world including a search for landing sites that could facilitate future in-situ exploration. The Europa Explorer is one such mission concept.

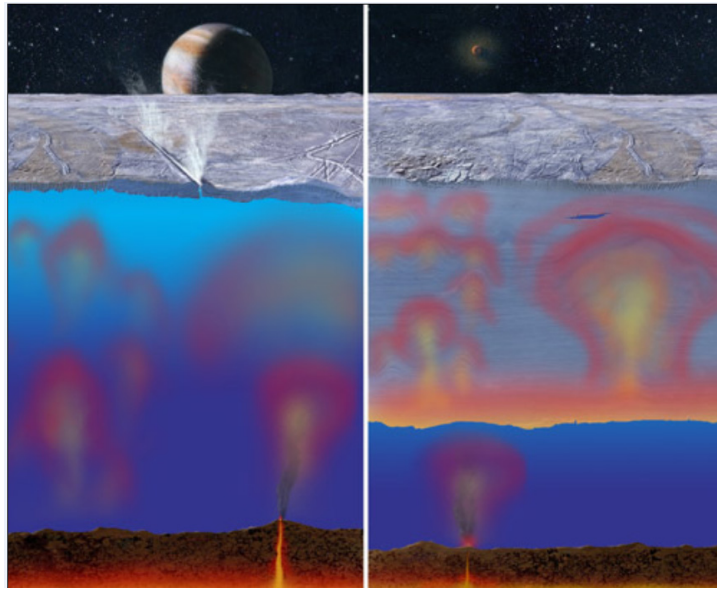
Europa, with a saltwater ocean beneath a thin cap of ice [1 and 2], is a high priority outer planet exploration target [3 through 5]. Figure 1 is a schematic, predicated upon available models [6].

Science objectives for a mission to Europa would include the following [1].

- Characterize the Europa ocean and deep interior, along with the ice shell and the nature of surface-ice-ocean exchange.
- Determine global surface compositions and chemistry, especially as related to habitability.
- Understand Europa's surface geology, and examine candidate sites for future *in situ* exploration.
- Characterize the magnetic environment of Europa as well as moon-particle interactions.
- Determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons.

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Figure 1 Schematic of Europa



The technical challenge to the conceptual Europa Explorer mission would be protecting the spacecraft from the harsh radiation environment [2]. The conventional approach to this problem would design the primary mission at Europa to end in just three or four months, resulting in a major operations challenge to complete primary science observations. There might be an extended mission, but its length or functionality could not be predicted. To relax pressure on system performance and enable extended observations, a longer primary mission at Europa is desired. Therefore, a series of trades were performed to understand the probability of the mission lasting past when conventional design practices would limit the prime mission. Among these trades was a decision to modify the Jet Propulsion Laboratory's (JPL's) historical approach to achieving mission life by transitioning from a purely deterministic paradigm to one explicitly including probabilistic assessments.

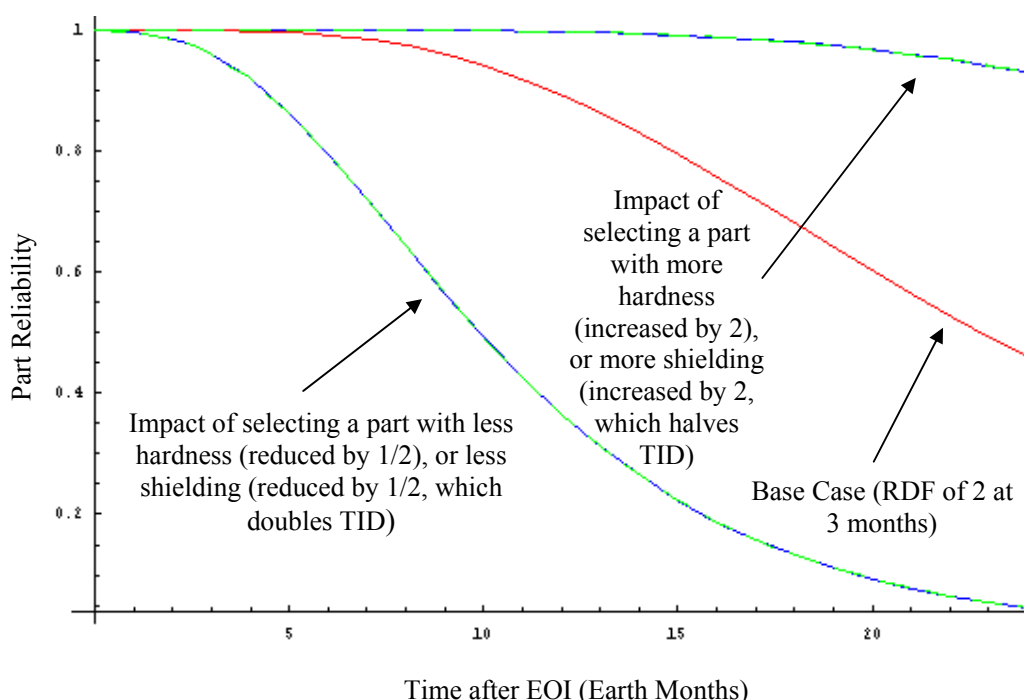
2 HISTORICAL APPROACH TO ACHIEVING MISSION LIFE

The conventional JPL approach for predicting mission life is codified in design principles [7]. As is customary with most engineering organizations, the design principles rely on the application of conservative margins. Separate sources of conservatism typically resulted in stacked margins. However, prior to assessing the mission life of the Europa Explorer the magnitude of the extra conservatism in these margins, and their impact on spacecraft reliability, had not been systematically examined.

An explanation of the conventional approach for predicting mission life is important because engineers cannot directly design to a probabilistic requirement, such as the time-dependent memory chip reliability, subsequent to Europa orbit insertion (EOI) depicted in Figure 2. Instead, the engineers identify the various stressing mechanisms that can cause a part to fail. For the majority of the electronic parts on the Europa Explorer the dominant stressing mechanism is the total ionizing dose (TID) received by a part. With respect to TID, the design principles [7] instruct designers to: determine the mean TID that the part will absorb over the mission lifetime; apply an appropriate radiation design factor (RDF);¹ and specify parts that have a rating greater than or equal to the product of the mean TID and RDF (or add shielding to reduce TID to the part's capability - typically with an

¹ Typically, a RDF of 2 is applied to electronic parts. However, parts that are highly tolerant of radiation (e.g., gallium arsenide parts) may have this requirement waived and operate with a RDF below 2. Radiation sensitive parts (e.g., MOSFETs and hybrids) are usually provided with a RDF in excess of 2.

Figure 2 Time-Dependent Reliability for a Typical CMOS Memory



increased RDF of 3, when spot shielding is necessary). Of course, the practice of part specification is highly iterative. First, there are factors the engineers must consider besides TID. Operating temperatures and duty cycles will, for example, also impact reliability. Moreover, engineers are not concerned merely with individual parts, but with ensembles of parts that form interacting circuits and subsystems.

Relative to just the TID considerations, designers may have a cost incentive to use less radiation resistant parts. In principle, the appropriate RDF can be furnished by adding shielding. Shielding, however, imparts a mass penalty on the spacecraft and, if exotic materials are used, may offer only limited cost savings. There are also limits to how much shielding can be beneficial, given secondary radiation effects and accompanying increases in uncertainty.

Using the conventional engineering approach, a Europa Explorer mission would have to be limited to just a few months in Europa orbit. It was understood that there were appreciable margins in these estimates, so the actual mission would probably function longer. Nevertheless, it was unknown how much longer the spacecraft might function.

Extending the primary mission life at Europa beyond a few months presented several challenges to JPL, such as understanding the margins inherent in previous design practices, performing interdisciplinary trades at an unprecedented level, and having greater reliance on autonomous spacecraft operation in order to more gracefully accommodate degradation. In addressing these challenges, however, the basic engineering processes inherent in the design principles [7] would have to be preserved.

3 PARTS OF THE PUZZLE

Parts of the puzzle (i.e., the spacecraft/mission facets that can be traded-off to optimize the Europa Explorer mission) are summarized in Table 1. In addition to these numerous facets there are possible trades among electronic part hardness, shielding, and reliability. Though only comprising a minor

Table 1: Parts of the Puzzle Relevant to Radiation

1.	Redundancy, cross-strapping, and fault containment
2.	Graceful degradation capabilities
3.	Diagnostic telemetry and supporting architecture
4.	Onboard dosimetry
5.	Mission trajectory
6.	Thermal design
7.	Circuit designs
8.	Part type selection

subset of the various trades performed, these three parameters are relevant because they succinctly illustrate how probabilistic techniques can be integrated into conventional design practices in a manner that both preserves current practice (i.e., the engineers perform their design studies in the usual manner) and extends the practice (i.e., the impacts of implicit margins can be quantified from the perspectives of reliability and risk).

Returning to Figure 2, the probability that a part fails is the probability that its TID exceeds its hardness. If: x_D is the TID received by an electronic part; x_H symbolizes the part hardness (relative to TID); t denotes time; and $f(x_D, x_H, t)$ signifies the joint probability density function for x_D and x_H at time, t ; then the time-dependent reliability, $R(t)$, of the part with respect to TID is:

$$R(t) = \int_0^{\infty} \int_{x_D}^{\infty} f(x_D, x_H, t) dx_H dx_D \quad (1)$$

This is merely a time-dependent version of the *stress-strength* models formulated in numerous references [e.g., 8 through 13].

Data demonstrate that the electron flux at Jupiter is lognormally distributed [14]. Since electrons dominate TID [15], a lognormal probability density function was used to approximate the uncertainty in TID subsequent to EOI, $\pi_D(x_D, t)$.² As such:

$$\pi_D(x_D, t) = \frac{1}{x_D \sigma_D \sqrt{2\pi}} \exp \left\{ -\frac{[\ln(x_D) - \mu_D]^2}{2\sigma_D^2} \right\} \quad (2)$$

According to shielding calculations [15], the TID three months after EOI would be almost twice as large as the TID at EOI, and the rate at which TID increases is linear, once in Europa orbit. If D_0 designates the mean TID at EOI (expressed as Mrad), and t is the time since EOI (in Earth months), then

$$\mu_D = \ln \left[D_0 \left(\frac{t}{3} + 1 \right) \right] - \frac{\sigma_D^2}{2} \quad (3)$$

It is inferred that σ_D is ~ 0.4 in the vicinity of Europa [14].

² Prior to EOI the impact of TID on part reliability is negligible, given conservative system design for a mission lasting at least that long. After EOI TID is the dominant failure mechanism, due to its large accumulation rate.

The derivation of Eq. 3 is predicated upon the constraint that the mean of the TID coincides with results from the shielding calculations [15]. This is important because mean dose is one of the parameters specified by the design principles summarized in Section 2.

A lognormal distribution also affords a reasonable approximation to the uncertainty in part hardness [1]. If the probability density function for part hardness is $\pi_H(x_H)$, then:

$$\pi_H(x_H) = \frac{1}{x_H \sigma_H \sqrt{2\pi}} \exp\left\{-\frac{[\ln(x_H) - \mu_H]^2}{2\sigma_H^2}\right\} \quad (4)$$

where the lognormal parameters satisfy the relationships:

$$\mu_H = \ln(H_R) - \frac{1}{2} \ln(C_{OV}^2 + 1) \quad (5)$$

and:

$$\sigma_H = \sqrt{\ln(C_{OV}^2 + 1)} \quad (6)$$

The variable, H_R , is the part hardness with respect to TID (in Mrad), while C_{OV} symbolizes the coefficient of variation in part hardness. With respect to Eq. 1, $f(x_D, x_H, t)$ is merely the product of $\pi_D(x_D, t)$ and $\pi_H(x_H)$.

Part hardness, as used in Eq. 5, typically exceeds the part rating cited by the manufacturer. This distinction is necessary because better manufacturers routinely ensure with high confidence that their parts will operate within specification well beyond the rating. This part margin, achieved through vendor test programs, is one of the conservative items inherent in the design principles [7]. Understanding such margins is essential for mission life prediction.

Given such relationships for these small but important puzzle pieces, an example of the trade-offs designers can perform at this part level is illustrated in Figure 2, which shows the sensitivity of reliability to changes in hardness or dose. For the base case (in red) the TID at EOI is 0.25 Mrad and the part hardness for TID is 2 Mrad.

4 THE PRELIMINARY RESULTS AND CHALLENGES

A mission study [1] has produced a conceptual design for the spacecraft. Relative to estimating the system-level reliability of electronic parts in the high radiation fields of Jupiter, there are two challenges:

1. quantifying the reliability of multiple parts at the assembly, subsystem, and system (i.e., spacecraft) levels; along with
2. modeling the various assemblies and subsystems that comprise the spacecraft engineering system for a design that is in early formulation.

With respect to quantifying the reliability of multiple parts in a high radiation field, the issue is the extent to which individual part reliabilities are correlated. Typically, reliability analyses invoke the supposition that the reliability of separate parts are independent. Thus, for N parts in series the overall reliability, $R_N(t)$, is the product of the individual part reliabilities and:

$$R_N(t) = \prod_{n=1}^N R_n(t) \quad (7)$$

Of course since each part reliability, $R_n(t)$, is less than unity, adding more parts to a series assembly decreases the overall assembly reliability.

Early in the mission the radiation dose has not accumulated to the level where it is a dominant contributor to part failure because there is a RDF of two at a design point after EOI. During these early mission phases an assumption of appreciable independence among part reliabilities (subject, of course, to conventional sources of common cause failure) is warranted. However, given the high dose rates in the Europa orbit, once radiation damage has reached a significant level it will strongly dominate the part reliability and could potentially show high correlation among parts if, for example, parts from the same lot or wafer are selected. For this hypothetical situation such correlated parts will fail at approximately the same time. Therefore, in the worst case:

$$R_N(t) = R_n(t) = R_1(t) = R_2(t) = \dots \quad (8)$$

For this condition there is no reliability penalty associated with assembling large numbers of parts in series. As a corollary, there would also be little reliability advantage to having parts in parallel (i.e., redundant hardware designs).

Given the sparseness of data regarding the extent to which part hardness and TID will be correlated, sensitivity studies and engineering judgment guided our assessment. This contributes to the epistemic uncertainty in our assessment results.

The Europa Explorer design and mission profile remain conceptual, so there is appreciable uncertainty in exactly how the various spacecraft assemblies and subsystems would be configured. For example, Eq. 8 suggests that redundancy may afford little reliability advantage subsequent to EOI. However, for the baseline mission trajectory selected the duration of the mission from launch to Jupiter orbit insertion (JOI) would be just over six years. During this interval the impact of deep space radiation on part reliability would be minimal.

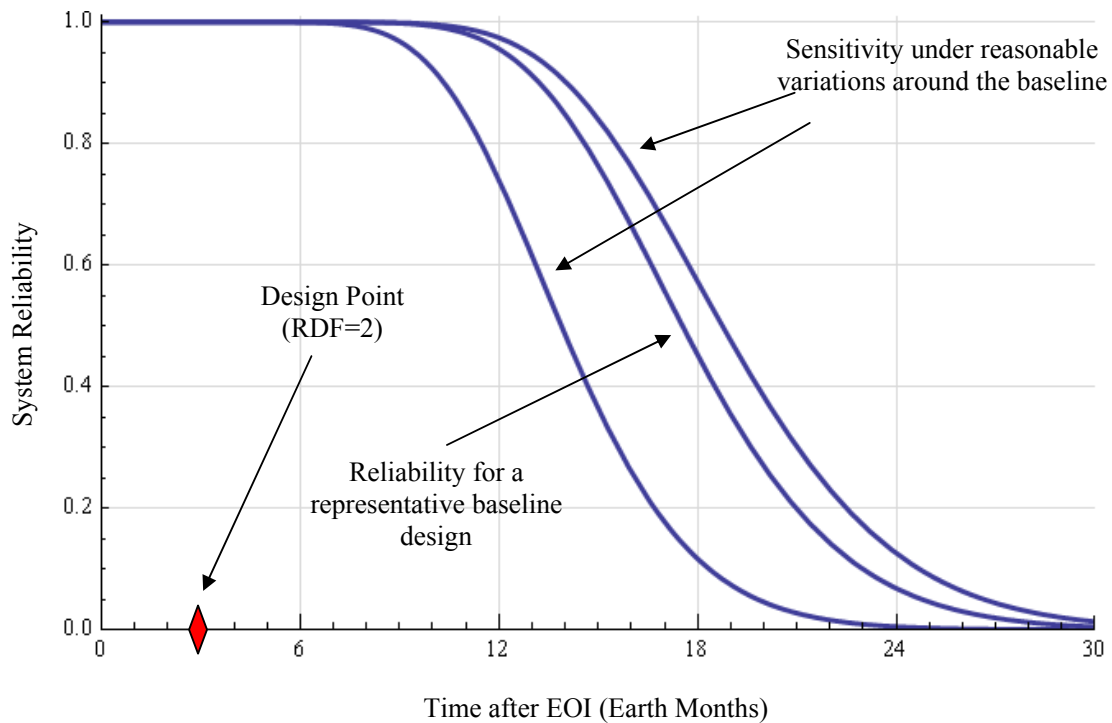
Figure 3 exhibits a spacecraft reliability estimate for the Europa Explorer mission concept. It depicts the design point,³ a reliability projection for a representative baseline design, and results of sensitivity studies for reasonable variations about the baseline design.

The variations about the baseline correspond to sensitivity studies addressing current uncertainties in our understanding of: the spacecraft design (e.g., the arrangement of the puzzle pieces listed in Table 1); along with how the Jovian radiation environment (especially after EOI) would degrade spacecraft reliability. As the design and our understanding of radiation effects on reliability evolve we expect the baseline reliability estimate to change, but huge variations are not anticipated. Even though the situation governing design of the Europa Explorer mission is challenging from both PRA and system engineering perspectives, we have the fundamentals of a methodology that enable us to perform the design trades necessary to achieve success. System engineering and PRA have been merged.

An appropriate perspective on the Figure 3 estimates is that they demonstrate the degree of confidence in a design process rather than representing a rigorous technical analysis of a specific flight system design. The deliberative process associated with development of Figure 3 involved discussing various flight system configurations, understanding failure mechanisms and modeling approaches, then integrating these with the techniques described in Sections 2 through 4. The result of this process is

³ Subsequent to completion of the assessment which resulted in Figure 3, the design point was increased to four months [1].

Figure 3 Estimates of the Flight System Level Reliability (with Qualitative Uncertainty Bounds)



that by instructing engineering staff to design the mission for a four month lifetime after EOI, the actual mission should endure for between one and two years. Consequently, the desire for a long duration Europa science mission would be achieved, and the conventional design process can be applied by the design team.

System engineers were involved with developing Figure 3. They understood and orchestrated the trade offs in mission concepts and implementation. Thus, the overall approach is compatible with engineering skills at both the system and part levels. The approach and results were favorably peer reviewed by independent experts from JPL and the Applied Physics Laboratory. Review involving a broader community is planned in the near future.

5 CONCLUSIONS

The approach reported in this paper is a feasibility study. Based on this effort, a new approach to estimate mission lifetime for space missions in a high radiation environment has been shown. This effort is founded on a rough model of the spacecraft and the science instruments it would carry. It is a first order estimate. Future efforts need to ensure model completeness, and obtain statistical data for reducing epistemic uncertainty. The future efforts and investments would be significant. They need to be accomplished over a period of time, and regular updates are required to enhance the model for current part test results and design decisions. This is needed so the model can support system trade studies for the implementation and operation phases of the project.

The needed future effort envisages potentially a full scope PRA. The environmental model will include other radiation effects besides TID, such as: displacement damage; particle directional information in the vicinity of Europa; transport analysis; and shielding models. For electronic parts and circuits, efforts will include: statistical properties of up-to-date parts used by the mission; statistical data on analog parts, hybrids and integrated circuits; as well as part degradation data.

This new approach is a paradigm shift for mission design. It is predicated upon a systems engineering perspective and PRA in estimating mission lifetime. The new approach must ultimately be integrated into design guidelines and requirements so that the project team can follow and implement it effectively.

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